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(54) Method of manufacture of an enhanced boiling surface heat transfer tube and the tube produced thereby

(57) A method of manufacturing an enhanced boiling surface heat transfer tube and the tube formed thereby includes the steps of forming fins (16) on the outer surface of a heat exchanger tube (15) by rolling, partially coining the fins on the tube utilizing knurling rolls (43), and finish coining the outer surface using burnishing rolls (44) to provide subsurface re-entrant cavities (33) in the tubing outer wall surface with re-entrant passages (34) communicating between the cavities and the tubing exterior surface.

Fig.14

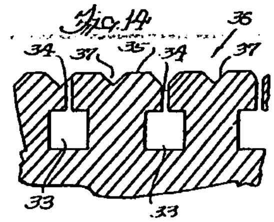
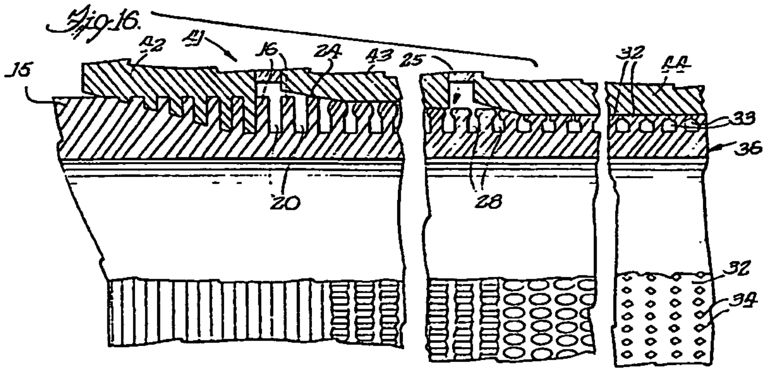


Fig.16.



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The drawing(s) originally filed was (were) informal and the print here reproduced is taken from a later filed formal copy.

Fig.1.

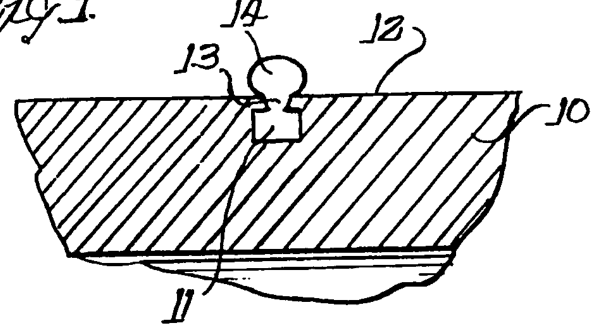
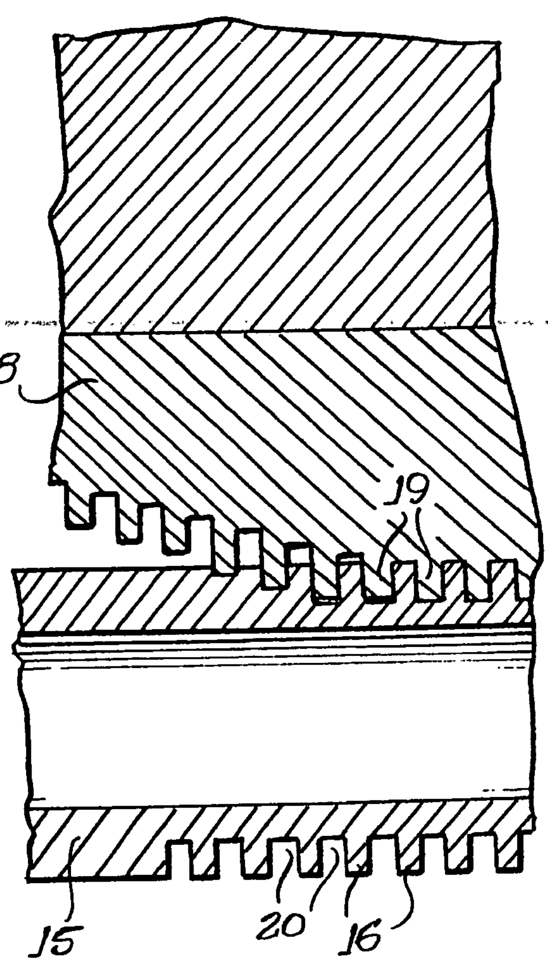


Fig.2.



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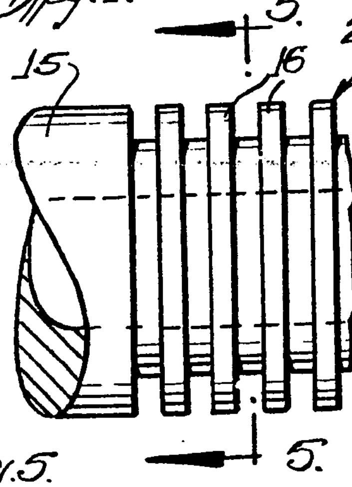

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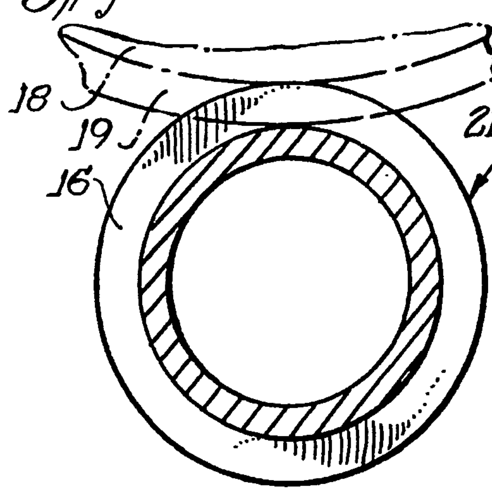

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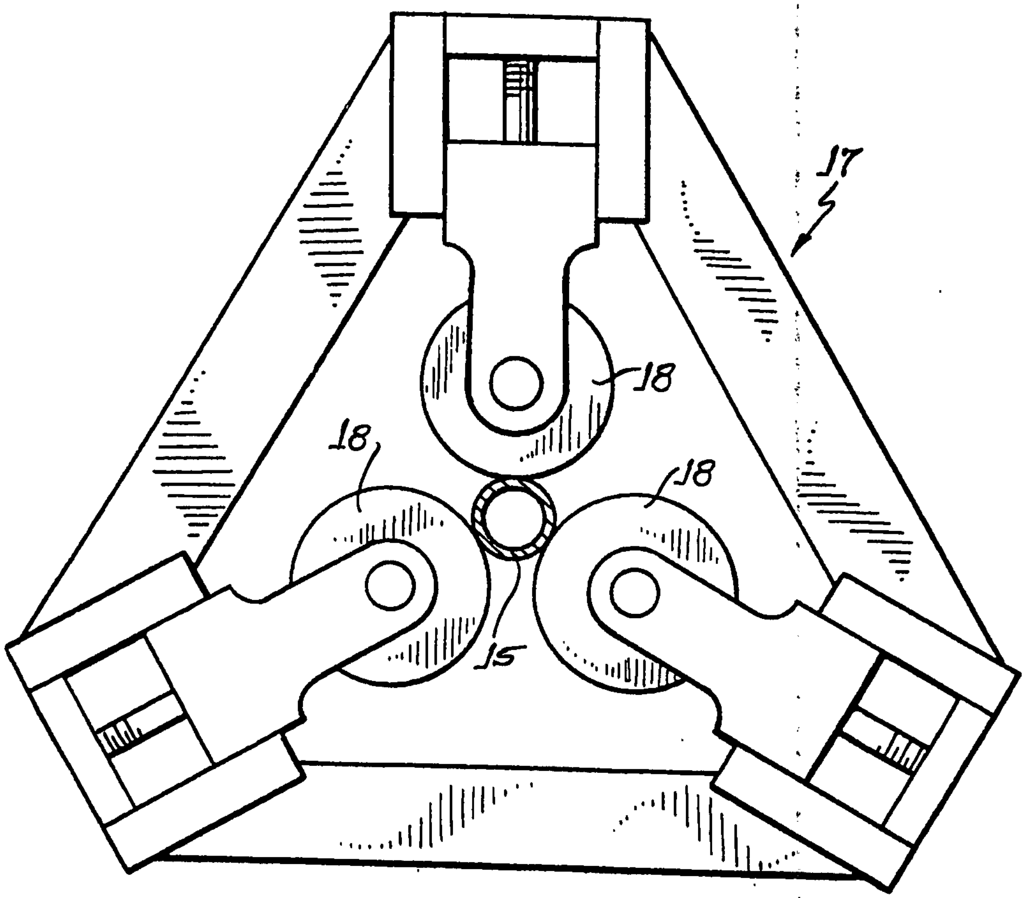

Fig. 15.

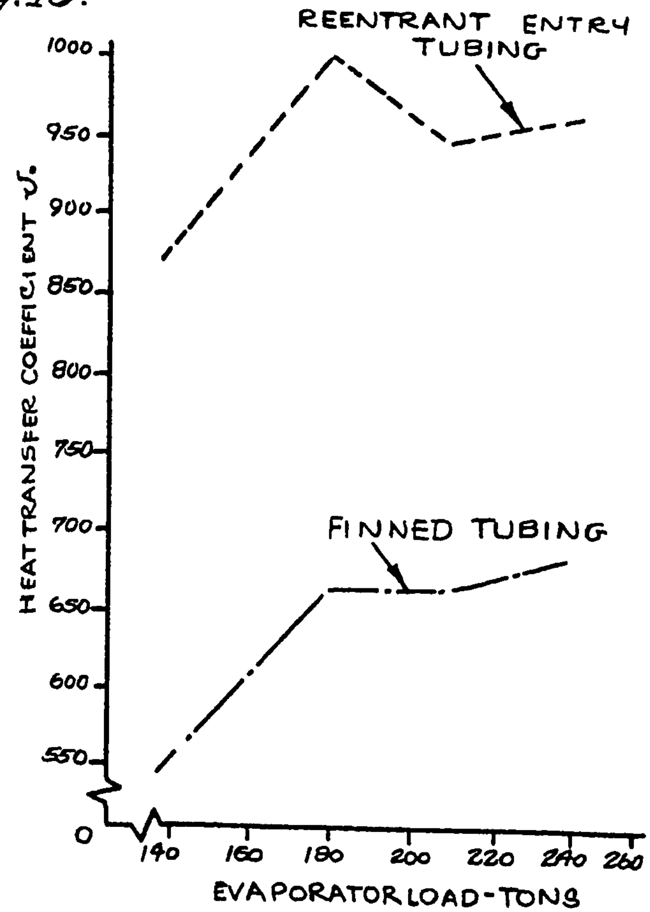

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Fig.6.

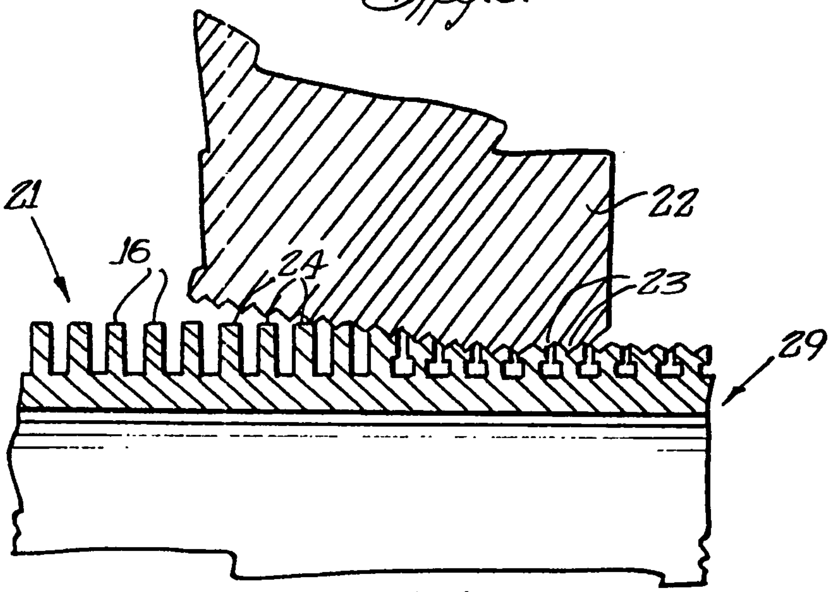
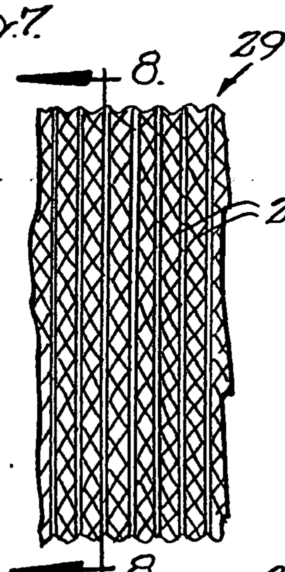


Fig.7.



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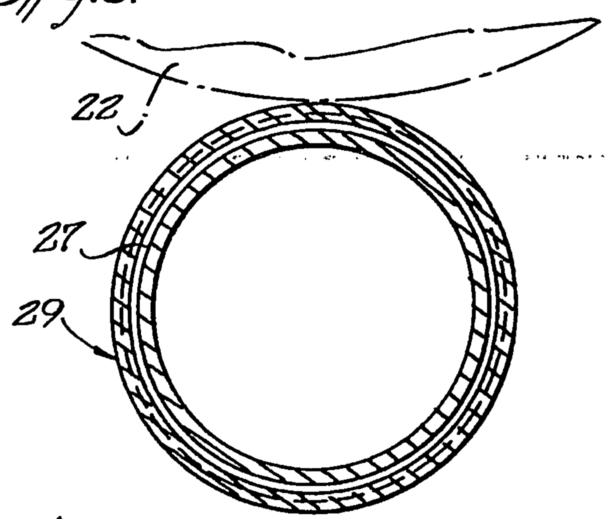


Fig.9.

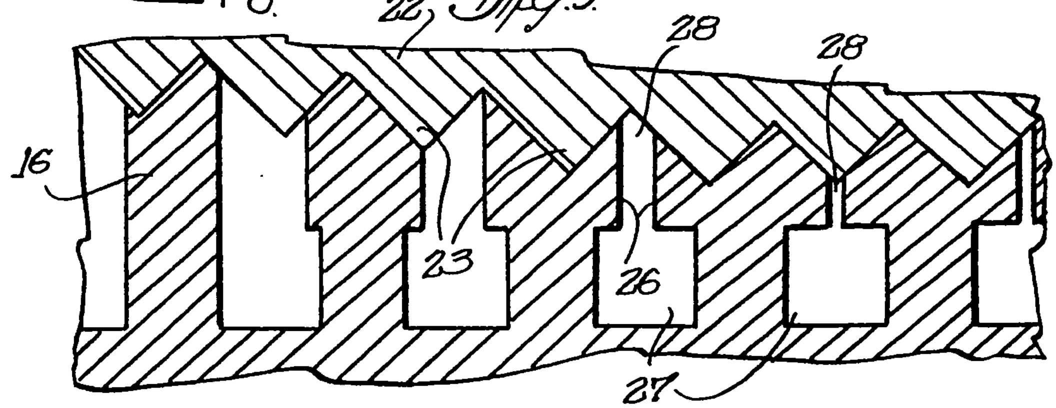
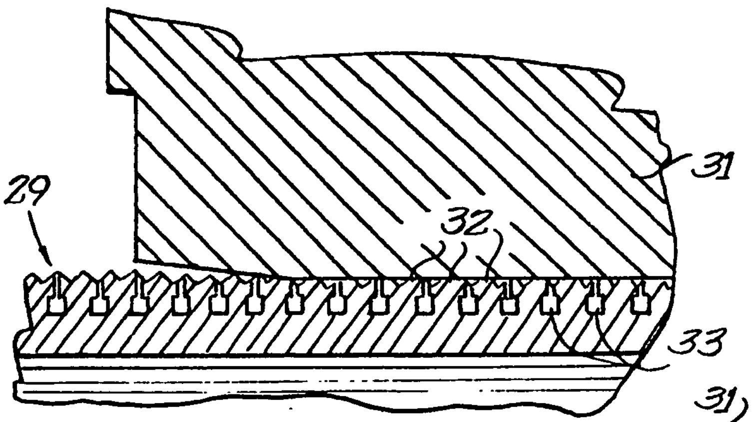


Fig.10.



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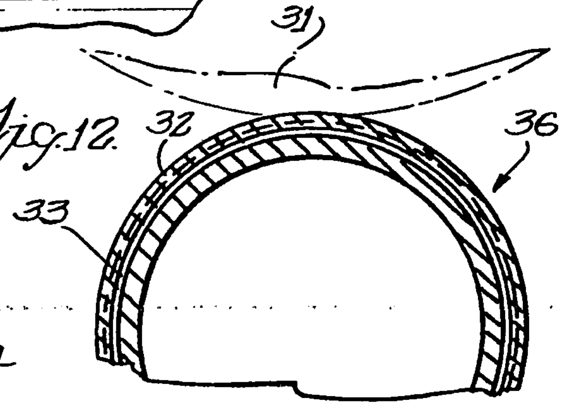


Fig.11.

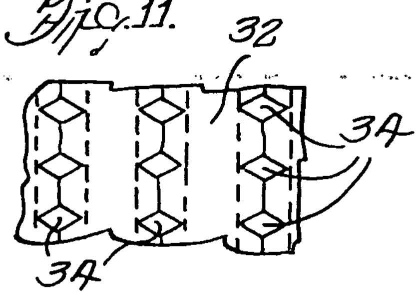


Fig.13.

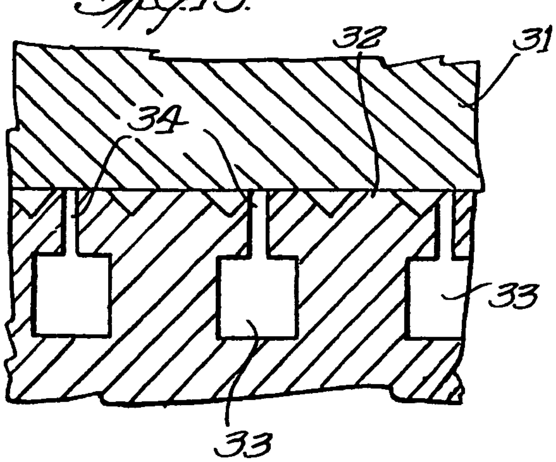
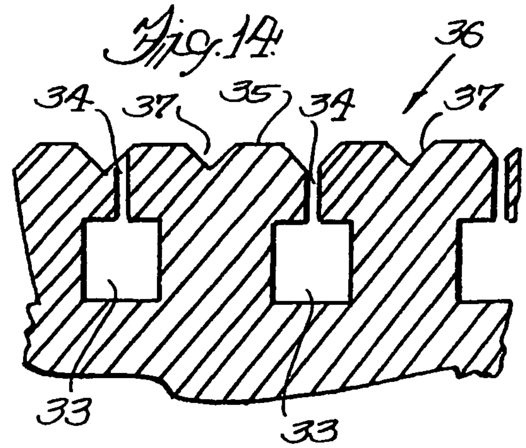


Fig.14.



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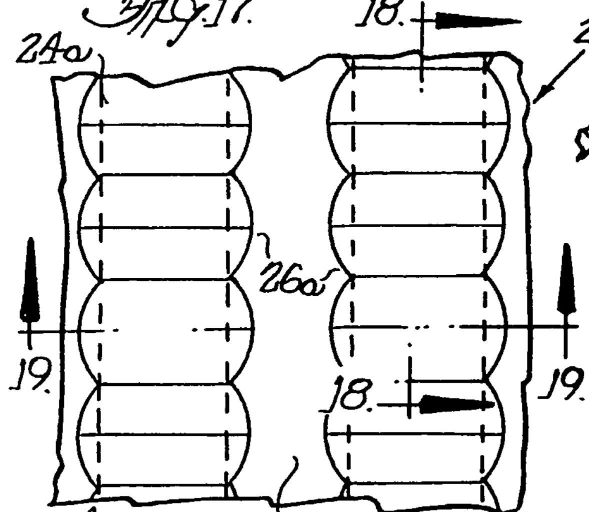

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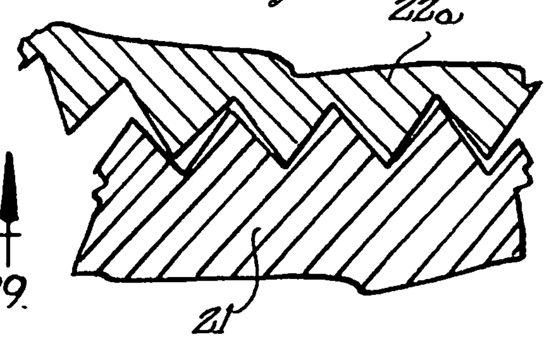
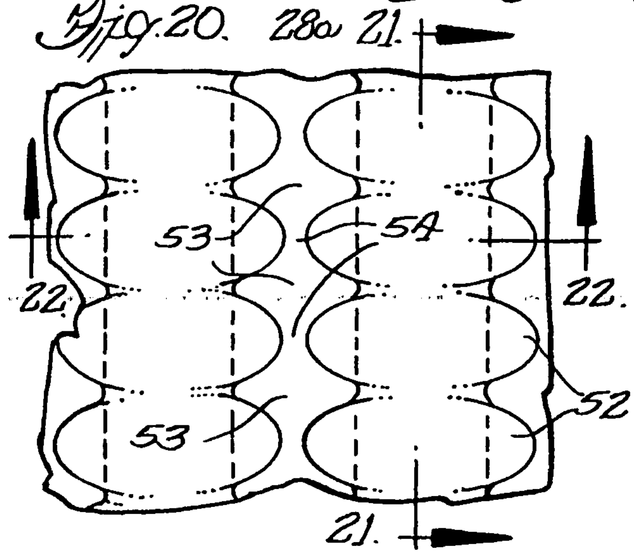


Fig. 20.



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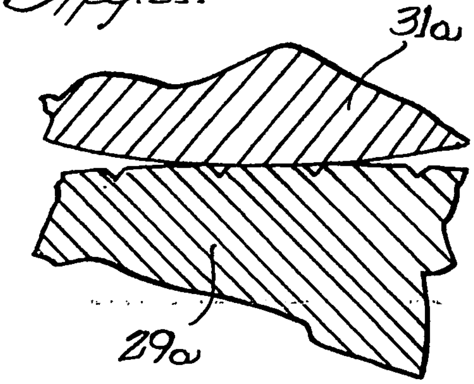
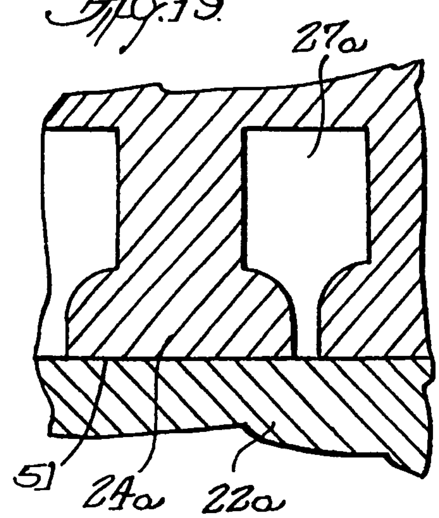


Fig. 19.



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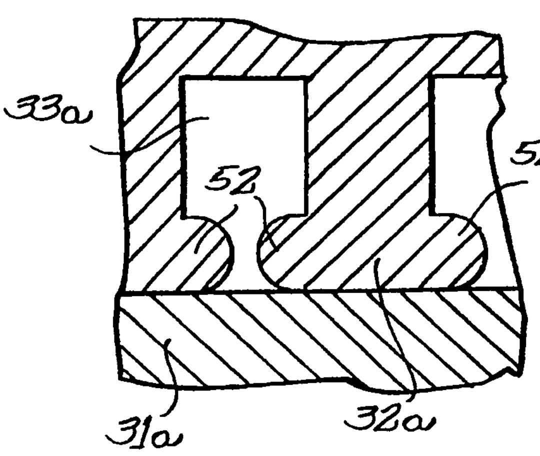


Fig. 23.

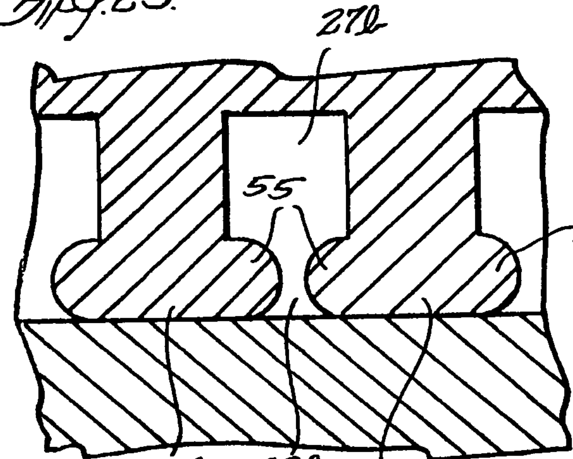


Fig. 24.

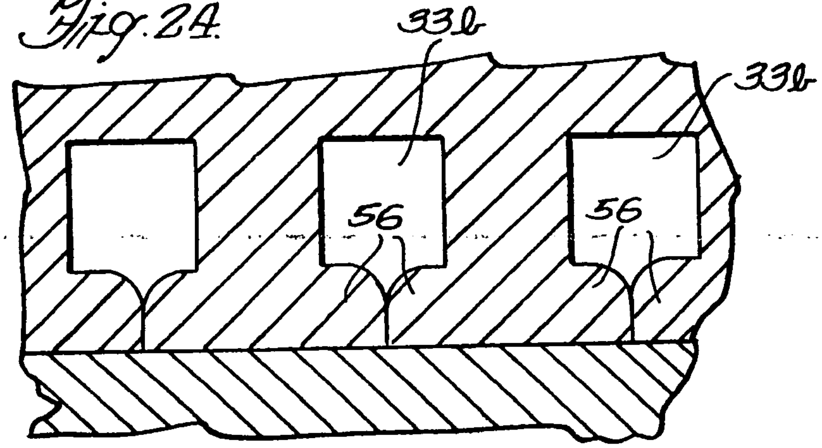


Fig. 25.

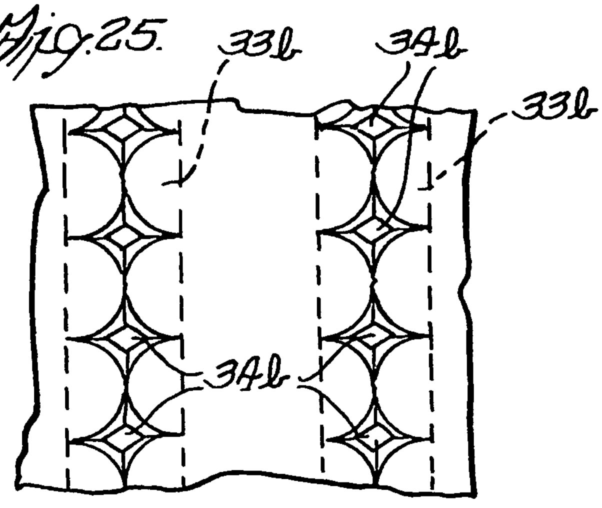


Fig. 26.

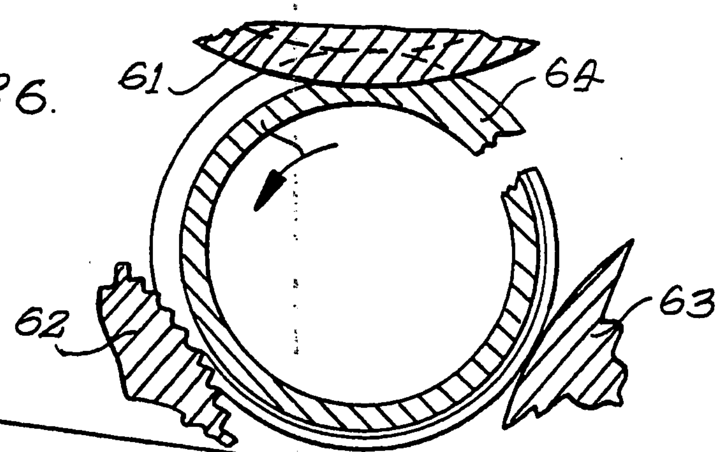
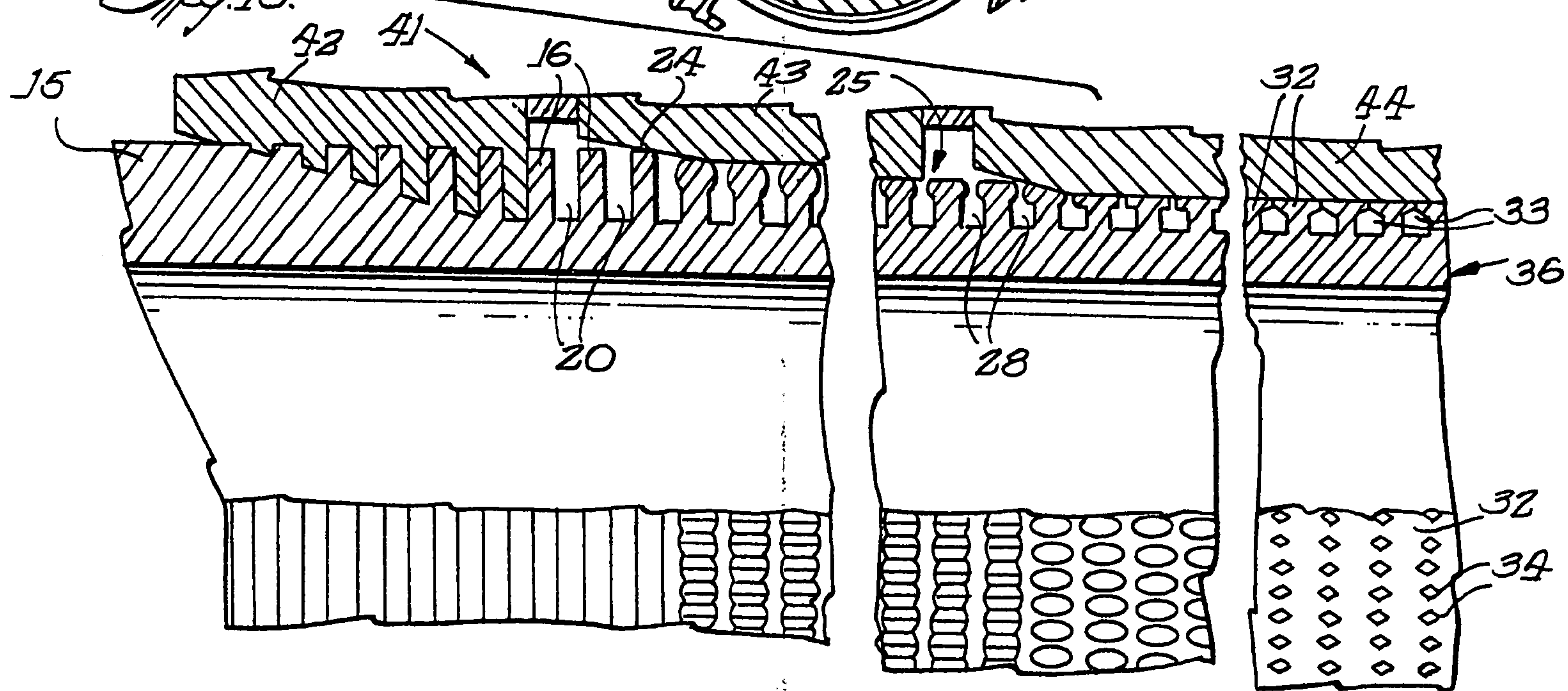


Fig. 16.



SPECIFICATION

Method of manufacture of an enhanced boiling surface heat transfer tube and the tube produced thereby

The present invention relates to the heat transfer wall of a tube having a heat-transmitting surface such as an evaporator tube for a water chiller which could be used for low or high pressure flooded evaporators.

One method of transferring heat from a heat transfer surface to a liquid contact with the surface is through nucleate boiling. This is a well known phenomenon wherein vapor bubbles are formed and rise from active areas on the heat transfer surface, known as nucleate boiling sites, as the surface temperature rises above the saturation temperature of the liquid. Nucleation occurs most vigorously at surface irregularities in which the vapor forming the bubbles may be trapped. Thus, nucleate boiling at a surface is improved when the heated wall portion through which heat is transmitted has a porous surface caused by the formation of cavities in the heated wall portion.

One method of providing these cavities comprises the deformation of the metal surface to form indentations therein and the electrodepositing a metal at the periphery of the craters from a special bath to provide honeycomb-like surfaces optimizing nucleate boiling augmentation. Also, the nodules electroplated on the surface may be flattened by cold-rolling to deform the surface and strengthen the nodules by work hardening.

Another method of improving the heat transfer characteristics of the tube surface is by grooving the surface at a fine pitch, forming notches in the resulting ridges, and then deforming or bending the edges of the ridges toward the deep grooves. This surface structure is formed by knurling the tube surface and subsequently machining the knurled surface by a cutting tool as if by plowing to form deep grooves alternating with ridges, with the edge of each ridge having shallower fine-pitch "V" notches.

The present invention provides an improved heat transfer surface and method of forming the same.

The present invention comprehends the provision of a novel method of forming a heat transfer tube with a surface acting to promote high heat transfer rates in nucleate boiling. In this method, subsurface re-entrant cavities are economically formed in the surface, with the cavities and re-entrant passage therefor progressively formed in the tubing surface by fin forming, notching and coining operations.

The present invention also comprehends the pr vision f a novel method of forming subsurface re-entrant cavities in the tubing wall by three progressions. In the first progression, fins are formed in the tube surface by rolling the tub in a thread rolling machine. In the second progression, the formed fins are notched and partially coined by rolling the finned tube in a thread rolling machine having a knurling die with diamond-shaped teeth r a straight knurl. The third progression takes the notched and partially coined fins tube by mashing the fins utilizing dies that are ground flat and polished to burnish the tube surface. The finished tube surface may be accomplished in three separate stages or progressions or in one rolling operation wherein all three dies are mounted on a single arbor and a single pass through the machine will completely form the tube.

The present invention further comprehends the provision of a novel heat transfer tube having subsurface re-entrant cavities to promote heat transfer rates in nucleate boiling. The cavities and discrete generally diamond-shaped holes forming re-entrant passages are formed by the progressively forming, notching and radially coining of standard metallic heat exchanger tubing.

Further objects are to provide a construction of maximum simplicity, efficiency, economy and ease of assembly, and such further objects, advantages and capabilities as will later more fully appear and are inherently possessed thereby.

Figure 1 is a partial cross sectional view of a tube wall containing an ideal subsurface re-entrant cavity.

Figure 2 is a partial enlarged cross sectional view of the first progression of an evaporator tube having fins rolled thereon.

Figure 3 is an end elevational view of the finned tube rolling die arrangement having three rolling dies.

Figure 4 is a partial elevational view of a heat transfer tube having fins rolled on a portion thereof.

Figure 5 is a cross sectional view taken on the line 5-5 of Figure 4.

Figure 6 is a partial enlarged cross sectional view of the second progression in forming the tube using a knurling die.

Figure 7 is a partial elevational view of the knurled tube.

Figure 8 is a cross sectional view taken on the line 8-8 of Figure 7.

Figure 9 is a greatly enlarged partial cross sectional view illustrating the knurling of the tube surface.

Figure 10 is a partial cross sectional view of the third progression in forming the tube with a burnishing die.

Figure 11 is an enlarged partial elevational view of the tube of Figure 5 showing the re-entrant openings.

Figure 12 is a partial cross sectional view of the burnished tube.

Figure 13 is a greatly enlarged cross sectional view of the burnishing operation.

Figure 14 is a partial cross sectional view of the finished tube.

Figure 15 is a graph illustrating the impr ved heat transfer characteristics of the tube f the pr sent invention.

Figure 16 is a partial cross sectional view of an evaporator tube being formed thr ugh the three progressions in a singl rolling operation.

Figure 17 is an enlarged partial side elevational

view of a knurled tube using a straight knurling die.

Figure 18 is an enlarged cross secti n view tak n on line 18-18 of Figure 17, but showing both the knurling die and tube wall.

Figure 19 is an enlarged cross sectional view taken on line 19-19 of Figure 17.

Figure 20 is an enlarged partial side elevational view of the tube of Figure 17 having a minimum burnish applied thereto.

Figure 21 is an enlarged cross sectional view taken on line 21-21 of Figure 20 showing both the tube wall and burnishing die.

Figure 22 is an enlarged cross sectional view taken on the line 22-22 of Figure 20.

Figure 23 is a cross sectional view similar to Figure 19 but for a maximum knurling operation.

Figure 24 is a cross sectional view similar to Figure 22 but for a maximum burnish.

Figure 25 is a partial side elevational view similar to Figure 20 but for the maximum burnish.

Figure 26 is a partial and elevational view of a rolling die arrangement having individual fin forming, knurling and burnishing dies on the three separate axes.

Referring more particularly to the disclosure in the drawings wherein are shown illustrative embodiments of the present invention, Figure 1 discloses a portion of a wall 10 of an evaporator tube having an idealized subsurface re-entrant cavity 11 therein communicating with the tube surface 12 by a narrowed re-entrant passage 13; the cavity width being greater than the width of the cavity re-entrant mouth. A study of nucleation from a single cavity indicates that cavity geometry is important in two ways. The mouth diameter determines the superheat required to initiate boiling and its shape determines its stability once boiling has begun. In boiling, bubbles 14 originate from preexisting vapor pockets in cavities on the surface, and it appears that the surface conditions can have a profound effect of the nucleation characteristics of the surface.

In nucleate boiling, the trapped vapor is superheated by the heat exchanger tube surface and consequently grows in size until surface tension is overcome and the vapor bubble 14 breaks free from the surface. As the bubble leaves the surface, liquid wets and now vacated surface and the remaining vapor has a source of additional liquid for creating more vapor to form the next bubble. The continual wetting and release together with the convection effect of the super heated bubbles travelling through and mixing the liquid results in an improved heat transfer rate for the heat exchanger surface. The surface heat transfer rate is high in the area where the vapor bubble is formed, and th overall heat transfer rate tends to increase with the density of vap r entrapment sites per unit area f heat exchanger surface. The cavities 11 allowing bubbles, which promote the nucl ate boiling of the liquid, to resid therein are formed on the tube surface 12 and communicate to outside space through the re-entrant passage or mouth 13 so as to ensure an excellent heat transf r performance.

With referenc t Figures 2 thr ugh 10, a novel method of forming an enhanced boiling surface heat transfer tube is illustrated for smo th r finned, drawn r weld d, metallic heat exchanger tubing 15. In the first step or progression, radial fins 16 are formed on the tubing 15 by rolling the tube in a standard thread rolling machine 17 with the tooling consisting of three fin rolling dies 18 set at angles of 120° relative to each other (Figure 3), radially around the tube to be fabricated with a 3° to 6° skew angle to feed the tubes through the machine; the desired fin configuration 19 (typically 20 to 40 fins per inch at a depth of 0.040 to 0.060 inch) being ground on the periphery of the dies. The dies are set in the thread rolling machine such that the fin height produced does not exceed the original outer diameter of the tube 15, forcing all metal displacement to be lateral. Rolling the tube between the dies imparts the fin form 16 to the resulting tube 21 with separating grooves 20 (Figures 2, 4 and 5).

In the second progression (Figures 6-9), the radial fins 16 on the tube 21 formed in the first progression are notched and radially coined by rolling the tubing in a similar thread rolling machine equipped with three notching and forming dies 22 set at angles of 120° relative to each other, radially around the tube with a 3° to 6° skew angle to feed the tubes through the machine. The desired configuration of the notching and forming dies (typically a series of four-sided sharp diamond points 23 which are 0.010 to 0.020 inch high with 60° to 90° included angles at the point) is helically ground on the periphery of the three dies with a pitch of 40 to 60 threads per inch. The dies are set in the machine such that the fin height is reduced 20 to 40 percent. This causes the metal displacement to be a lateral thickening (coining) of the tips 24 of the fins and imparts a notched surface 25 to the periphery and sides 26 of the tubing fins (Figure 9).

Since the surface of the notching and coining roll dies 22 are a series of four-sided diamond points 23, the forming and coining compressive load on the tubing will not be severe. The rolling pressure is applied gradually as the die points penetrate the tubing surface (Figure 6), greatly reducing the tendency of the tube to collapse. Therefore, internal support for the tube, such as an arbor, is not required and substantially reduces the complexity of the operation. The thickening of the fins 16 partially forms the re-entrant cavity 27 within the fin slots 20 of the heat exchanger tubing and also produces notched radial channels 28 leading into the cavities (Figure 9) forming an intermediate tube 29.

In the third progression (Figures 10-13), the coined and notched radial fins on the tubing 29 formed in the second progression are finish coined by rolling the tubing in a third thread rolling machine equipped with three forming dies 31 set at angles f 120° relative to each other (similar to Figure 3), radially around th tub to be fabricat d with a 3° to 6° skew angle to feed th tubes through the machine. Th desir d configuration of the dies is ground on the periph ry thereof; th configuration comprising radial dies gr und flat

and p lished to impart a burnished finish to the periphery of th tubing. The dies 31 are set in the machine such that the fin height is reduced a further 10 to 20 percent; causing the metal displacement to be lateral, further thickening (coining) the already coined fin tips 32. With the further thickening of the fin tips, the channels 28 between the notched fins collapse, sealing the formed re-entrant cavities 33, except in those areas where the notched sides 26 of the fins meet. In these areas, small diamond-shaped holes 34 (Figure 11), not exceeding 0.010 inch in diameter, will be formed which constitute the re-entrant passages to the circumferential cavities 33. The periphery 35 of the finished tube 36 will have a smooth, burnished surface with many very small, diamond-shaped dimples 37 caused by the previous notching operation and only partially filled by the metal flow resulting from this progression.

As seen in Figure 15, the re-entrant cavity tubing as formed by the above process provides a significant increase in the heat transfer coefficient over that of conventional finned tubing in heat exchanger tube bundle tests. This improvement in heat transfer coefficient means that for a given evaporator load, fewer re-entrant cavity heat exchanger tubes will be required per tube bundle than with conventional finned heat exchanger tubes. Thus, the tube bundle cost is substantially reduced as there is no increase in manufacturing costs for fabricating re-entrant cavity tubes over finned tubes.

The heat transfer coefficient for the tubes fabricated by the present method is improved by increasing the efficiency of the nucleate boiling process. Since the evaporation of fluids largely takes place in the subsurface, circumferential cavities 33 of the tube 36, the product of the evaporation-vapor bubbles will form at the mouth of the small, diamond-shaped holes 34 which are the re-entrant passages to the cavities. As the small vapor bubbles detach themselves continuously from the mouth of the holes in a stream, the liquid in the cavities is replenished by being drawn into the holes by the slight vacuum produced when the liquid is evaporated. This process is enhanced when the evaporator tubes are lying in the preferred horizontal position. In this instance, the vapor bubbles escape from holes located on the top surface of the tube, while the liquid is drawn into holes located on the bottom surface of the tube. The process continues with the nucleation energy remaining minimal.

Since there are no slots other large openings leading into the cavities, only the small holes with diameters less than the diameters of the vapor bubbles, the vapor bubbles coming from the tube cannot enter the cavities of an adjacent tub to interfere with the boiling process of the second tube. The substantially smooth burnished surface of the tube after fabrication has no surfaces that will interfere with the stream of vapor bubbles being given off by adjacent tubes. The stream of vapor bubbles from one tube will simply be deflected by other tubes without interfering with their flow. The smooth tube surfaces and small re-entrant passages, therefore, greatly minimize the vapor bubble generation interaction between adjacent tubes. This is particularly significant when the tubes ar placed close together as in a tube bundle in a heat exchanger shell.

Another significant cost savings in using the re-entrant cavity tubing over finned tubing is in material handling and tube insertion into bundles. The re-entrant cavity tubing has a smooth, dense surface making them much less susceptible to damage in handling and insertion than the fragile fins on the surface of finned tubing.

Although the tubing manufacture has been disclosed as run in three single passes through a thread rolling machine with each pass being one progression, if finned tubing is utilized, then only the second and third progressions are required in two single passes through a thread rolling machine.

In a preferred method, smooth, drawn or welded heat exchanger tubing is run in one pass through three progressions in a thread rolling machine 41 illustrated in Figure 16. The three sets of three rolling dies 42, 43 and 44 are mounted on three common arbors in the thread rolling machine, and the re-entrant cavities are formed in the tubing in one pass at a manufacturing cost not exceeding that of rolled fin tubing. Also, if a previously finned tube is utilized, the final tubing may be formed in one pass through the machine using only the dies 43 and 44 to provide the second and third progressions.

Figures 17 through 22 disclose a similar tube forming operation utilizing straight knurling dies 22a as seen in Figure 18. A finned tube, such as the tube 21 of Figure 4, is fed through the straight knurling dies 22a to cause metal displacement of the outer ends 24a of the fins to provide a generally grooved surface with widened end portions 51 as seen in Figure 19 for approximately 20 percent reduction of fin height. The reduction in fin height results in partial closure of the radial channels 27a with slightly notched sides 26a.

The knurled tube 29a is fed through a third die progression of burnishing dies 31a (Figure 21) to burnish and finish coining the tubing to further compress the upset fin ends for an additional 10 percent. The metal of the knurled fin tips 32a has further lateral displacement, as at 52, to additionally close the channels 28a between the upset fins to provide cavities 33a with substantially continuous diamond-shaped reentrant openings 53 which are joined together by narrow necks 54 providing an open groove.

Figure 23 through 25 disclose second and third progressions of a finned tube utilizing maximum knurling and burnishing operations. As seen in Figure 23, a maximum burnishing causes an approximately 40 percent reduction in the fin height by lateral displacement 55 of th outer fin nds 24b to partially close the channels 28b between the fins. Then, th burnishing of the knurled fins provid s an additi nal 20 per cent reduction in the fin height with additional lateral displacement at 56 and substantially complete closure of the channels t form

the re-entrant cavities 33b with substantially diam nd-shaped openings 34b (Figur 25).

A further r lling arrangem nt is gen rally sh wn in Figure 26 where th three dies in an arrangement like that shown in Figure 3, with a fin forming die 61 on one axis, a knurling die 62 on a second axis, and a burnishing die 63 on the third axis, a tube 64 thus has the complete re-entrant cavity configuration formed in one pass through the machine, with the forming surfaces of the dies 61, 62 and 63 being longitudinally spaced in the machine to provide a forming progression in a much shorter length of run of the tubing than the previous assemblies.

There are four distinct advantages for re-entrant cavity heat exchanger tubing that make it unique and inexpensive to fabricate, as well as being directly responsible for the enhancement of the heat transfer coefficient of this tube:

1. Sealed subsurface circumferential cavities in the tube.
2. Small (less than 0.010 inch diameter) re-entrant passages or openings leading into cavities.
3. Smooth burnished finish on the tube surface.
4. Tube formed by lateral metal displacement in one pass (preferably) through a thread rolling machine.

The tubes formed by this process are especially suited for flooded evaporator tubes for centrifugal water chillers or similar heat transfer structures.

CLAIMS

1. A method of forming a heat transfer tube having an enhanced boiling surface thereon comprising the steps of forming fins on metal tubing extending upward to outer edges, contacting the outer edges with a knurling die to progressively compress the fins and laterally displace the metal thereof thereby forming circumferential cavities between the fins with narrowed openings, and contacting the displaced metal with a burnishing die to further progressively compress and laterally displace the metal to substantially close said narrowed openings communicating with said cavities, said burnishing die forming a substantially smooth hard surface on said tube.

2. A method of forming a heat transfer tube as set forth in Claim 1, in which said knurling operation forms grooves in the side walls of the narrowed openings which result in generally diamond-shaped re-entrant openings upon the burnishing operation.

3. A method of forming a heat transfer tube as set forth in Claim 1, in which the fins resulting from said fin forming operation have an external diameter not exceeding the external diameter of th initial metal tubing.

4. A method of forming a heat transfer tube as set forth in Claim 1, wherein said knurling operation reduces the fin h ight in the range f 20 to 40 percent.

5. A method of forming a heat transfer tube as set forth in Claim 4, in which said burnishing operation reduces the fin height by an additional 10 to 20 percent.

6. A method f f rming a h at transfer tube as set forth in Claim 2, in which said re-entrant openings to not exceed 0.010 inches in diameter.

7. A method of forming a heat transfer tube as set forth in Claim 1, in which said metal tube is progressively finned, knurled and burnished in a single pass.

8. A method of forming a heat transfer tube as set forth in Claim 1, in which said fin forming and burnishing dies provide a spiral pattern on the metal tube.

9. A method of forming a heat transfer tube as set forth in Claim 1, in which said minimum knurling and burnishing operations result in a narrowed re-entrant channel communicating with said cavities.

10. A method of forming a heat transfer tube having an enhanced boiling surface thereon comprising the steps of obtaining finned metal tubing with the fins extending upward to outer edges, contacting the outer edges with a knurling die to progressively compress the fins and laterally displace the metal thereof thereby forming circumferential cavities between the fins with narrowed openings, and contacting the displaced metal with a burnishing die to further progressively compress and laterally displace the metal to substantially close said narrowed openings except for small re-entrant channels or openings communicating with said cavities, said burnishing die forming substantially smooth hard surface on said tube.

11. A heat transfer tube having a heat exchange exterior surface including substantially continuous subsurface cavities enclosed by deformed metal except for spaced small generally diamond-shaped re-entrant openings communicating therewith, the width of the cavities substantially exceeding the diameter of an opening, and the exterior of the tube has a generally smooth burnished surface.

12. A heat transfer tube as set forth in Claim 11 in which said cavities result from fins formed on the tube which are compressed to cause lateral displacement of the fin metal, said cavities being formed at the roots of the fins, and the re-entrant openings are formed between the abutting surfaces of the laterally displaced fin material.

13. A heat transfer tube as set forth in Claim 12, wherein notches are formed on the upper ends and sides of the fins during compression and metal displacement by knurling dies.

14. A heat transfer tube as set forth in Claim 13, in which diamond-shaped depressions are formed by the knurling dies, and the notches in the sides of the fins form the diamond-shaped re-entrant openings in the abutting fin surfaces caused by lateral metal displacement.

15. A heat transfer tube as set forth in Claim 11, wherein said re-entrant openings ar j in d by narrowed neck porti ns to result in a continuous irregular channel with the surface of th fins ut of abutment.

16. Apparatus for progr ssiv ly forming a heat transf r surface on a heat exchange tube comprising a set of fin forming dies supporting the tub

and progressively f rming spiral fins n the tube, a set of knurling dies t compress the fins and cause lateral displacement of the fin material, and a set of burnishing dies to cause further lateral metal displacement of the fins resulting in substantially continuous subsurface cavities with re-entrant openings in the tube surfaces communicating therewith.

17. Apparatus as set forth in Claim 16, wherein said fin forming, knurling and burnishing dies are mounted on common arbors so that the tube is progressively formed in one pass through the apparatus.

18. Apparatus as set forth in Claim 16, in which said fin forming dies provide fins on the tube whose diameters do not exceed the original diameter of the tube.

19. Apparatus as set forth in Claim 16, wherein knurling dies have small four-sided diamond points.

20. A method of forming a heat transfer tube substantially as hereinbefore described with the reference to the accompanying drawings.

21. A heat transfer tube constructed and arranged substantially as hereinbefore described with reference to and as illustrated in the accompanying drawings.

22. An apparatus for progressively forming a heat transfer surface on a heat exchange tube constructed and arranged to operate substantially as hereinbefore described with reference to and as illustrated in the accompanying drawings.

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